Pacific Northwest NATIONAL LABORATORY

PNNL-30190

Biopower:

The Impact of Deploying Biofuels to Replace Petroleum Liquids in Stationary Power Applications

July 2020

JA Askander
SB Jones
CJ Freeman
MH Langholtz
N Samu

U.S. DEPARTMENT OF ENERGY

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Pacific Northwest National Laboratory
Richland, Washington 99354

[1] Oak Ridge National Laboratory, Oak Ridge, Tennessee

Executive Summary

Petroleum-based liquids are used in some power-generation applications in the United States, predominantly in the New England, Middle Atlantic, South Atlantic, and Pacific Noncontiguous regions. Power plants that burn petroleum liquids, such as distillate or residual fuel oils, are generally used for short periods to accommodate peak electricity demands. The U.S. Energy Information Administration estimated the U.S. consumption of petroleum liquids for electricity generation at 27 million barrels in 2018, representing a cost of $2.4 billion annually (EIA n.d.-b). This study assesses the potential to displace all or part of the petroleum liquids used for U.S. power generation with biofuels. The biofuels for this application are assumed to be derived from terrestrial feedstocks, with conversion routes of both fast pyrolysis (bio-oil) and hydrothermal liquefaction (biocrude).

In this work, regional models were used to assess the availability and cost of three different feedstocks: clean wood, forest residues, and corn stover, each of which has been assessed in the laboratory at small or pilot scales for conversion to bio-oil or biocrude. The estimated biofuel production values are based on equivalent heat energy versus current heavy fuels. Figure ES.1 shows the availability estimates for each biomass type for each U.S. census division using a conservative feedstock price (in each case) of $80 per dry tonne. Overlaid on these data are the corresponding estimates of how much of each biomass type would be required to supply the current petroleum-liquid power-generation plants in that region. For conservatism, hydrothermal liquefaction biocrude processing was assumed in the estimates, because significantly more overall biomass is required than for pyrolysis-based bio-oil (1.1 to 1.7 times, depending on the feedstock).

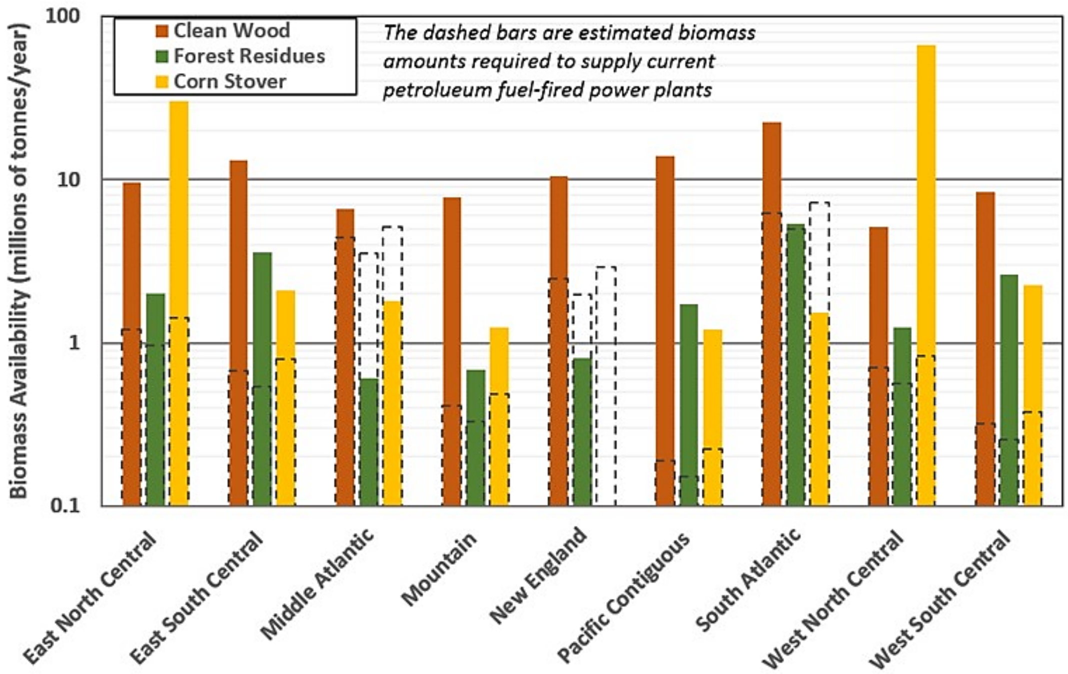

Figure ES.1. Biomass Availability for U.S. Census Divisions, along with Required Amounts for Each Respective Region's Petroleum Fuel-Fired Power Plants (dashed bars).

The data in Figure ES.1 show that the petroleum-liquid power generation in each of the census divisions could be supplied by one or more of the feedstocks evaluated. For all regions, clean wood supplies alone could potentially provide ample supply. For all but two regions (Middle Atlantic and New England) forest residues, alone are potentially sufficient. Finally, for all regions but three (Middle Atlantic, New England, and South Atlantic), corn stover, alone, is potentially sufficient.

The minimum fuel selling prices (MFSPs) of bio-oil and biocrude were estimated for each feedstock type and census division. This analysis showed that fast pyrolysis bio-oil projections would be lower (14% on average) than current wholesale petroleum-based heating oil prices in each of the regions, assuming 100 dry tonnes/day processing capacity. However, biocrude cost predictions were significantly higher in all cases because corresponding conversion yields are lower than those for bio-oil. Figure ES.2 shows the estimated MFSPs for produced bio-oil and biocrude relative to biorefinery capacity. This plot shows that the most significant decrease in MFSP occurs with an initial capacity increase from 100 to 500 tonne/day.

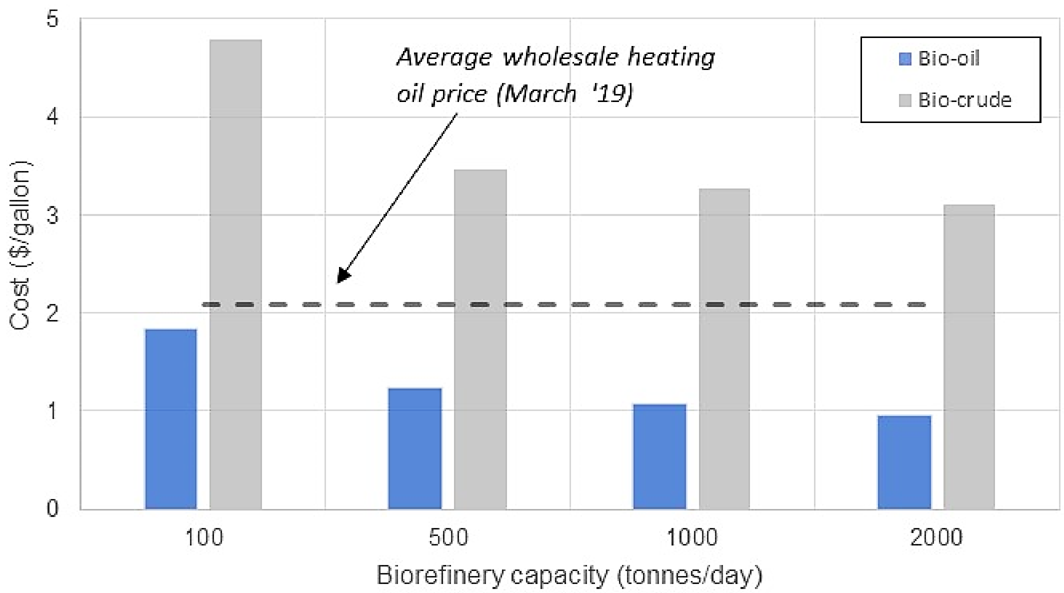

Figure ES.2. Estimated Biofuel Costs Relative to Refinery Capacities. Clean wood feedstock assumed at $84/dry tonne.

Based on the preliminary results of this study, it is apparent the biofuels could be an economical alternative to current petroleum liquids in U.S. power generation. However, more research is needed to determine the biofuel characteristics necessary to support current generation equipment. Stakeholders in both power generation and biofuel production stakeholders should be engaged to outline the research and testing needed to identify the technical hurdles to capitalizing on the opportunity.

Acronyms and Abbreviations

EIA	Energy Information Administration
GFN	Green Fuel Nordic
HTL	hydrothermal liquefaction
LHV	lower heating value
MFSP	minimum fuel selling price
POLYSYS	Policy Analysis System (model)
RTP	Ensyn's Rapid Thermal Processing (RTP™) technology

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1.0 Introduction

This study analyzes the opportunity of using biofuels to replace all or part of the petroleum-liquids fuels used in current U.S. power generation. For this study, three types of feedstocks were evaluated, with two different possible conversion technologies: fast pyrolysis bio-oil or hydrothermal liquefaction (HTL) biocrude. No significant post-treatment of the bio-oil or biocrude was assumed. The feedstocks assessed were clean wood, forest residues, and corn stover, most of which have been researched at the laboratory at small or pilot scales for conversion to bio-oils or biocrudes. Fast pyrolysis of clean wood is commercially available today.

2.0 Liquid Fuel Use in U.S. Power Generation

In 2018, the U.S. Energy Information Administration (EIA) estimated that 4.2 trillion kWh of electricity was generated at utility-scale electricity generation facilities in the United States (EIA n.d.-b). 63% of this electricity generation was from fossil fuels (coal, natural gas, petroleum, and other gases). Petroleum liquids include distillate fuel oil and residual fuel oil and contributed 0.4% of the total generation in 2018 (see Appendix A). Table 1 lists the net annual electricity generation and fuel consumption from petroleum liquids over the past three years. These data show the total U.S. petroleum liquids fuel usage for all power sectors in 2018 was 27,245 thousand barrels. The average price of oil in March 2019 was $2.09 per gallon($87.78/barrel). Using this pricing, the total cost of petroleum-liquid pricing for U.S. power production is approximately $2.4 billion per year.

Table 1. Net Electricity Generation and Fuel Consumption for Petroleum-Liquid-Based U.S. Power Generation (EIA n.d.-b)

	2016		2017		2018	
	Annual Energy (billions of kWh)	Liquid Fuel Volume (thousands of barrels)	Annual Energy (billions of kWh)	Liquid Fuel Volume (thousands of barrels)	Annual Energy (billions of kWh)	Liquid Fuel Volume (thousands of barrels)
All Electricity Sectors	12.8	22,405	12.4	21,696	15.6	27,245
Electric Utilities	9.3	16,137	8.9	15,567	10.2	17,733
Independent Power Producers	3.3	5,624	3.1	5,461	5.0	8,692
All Commercial	0.1	108	0.1	191	0.2	281
All Industrial	0.3	536	0.3	476	0.3	539

Figure 1 shows the distribution of petroleum-liquid-based power plants in the U.S. Roughly 70% of existing petroleum-fired electric generating capacity was constructed before 1980 (EIA 2017), and will soon be retired. Utility-scale generators that reported petroleum as their primary fuel were only 3% of the total electricity-generating capacity at the end of 2016. These generators now produce less than 0.4% (EIA 2018). Of the 36 gigawatts of remaining petroleum-fired generating capacity, more than 68% is contained within ten states, primarily coastal states with access to marine ports.

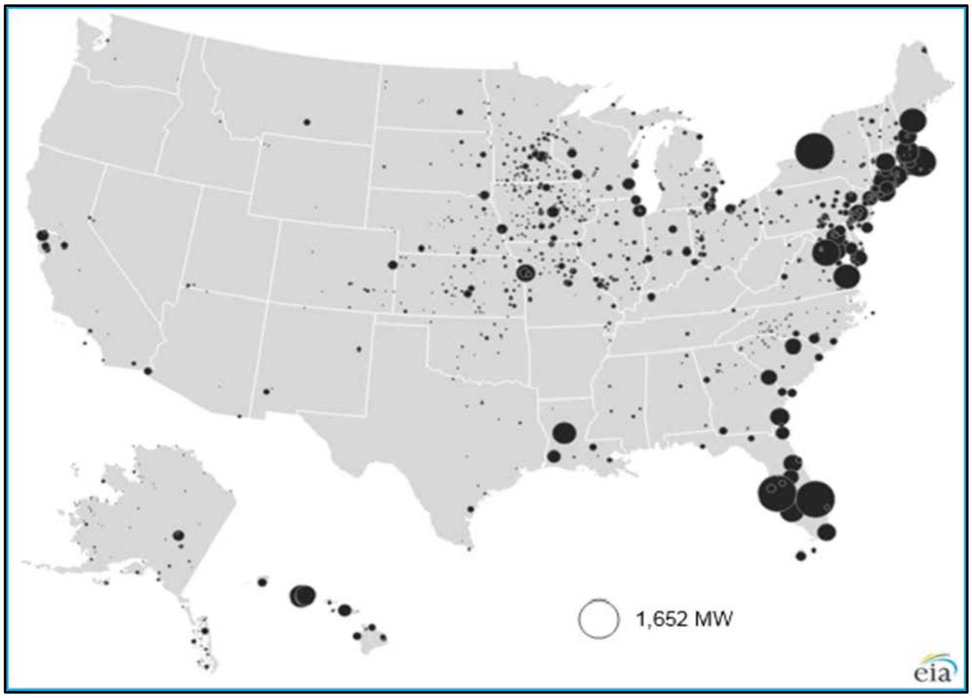

Figure 1. Distribution of Petroleum-Liquid-Based Power Plants in the U.S. (2016). The size of the bubbles corresponds to the amount of power generation (EIA 2017).

Power plants that burn petroleum liquids, such as distillate or residual fuel oils, are generally used for short periods during times of peak electricity demand. Most oil-fired generators in the U.S. are either turbines or internal combustion engines. They are used to supply power only during peak demand or when natural gas prices rise considerably along with local natural gas demand, such as in winter months. In these cases, petroleum-fired power plants operate mostly at low capacity factors because of the high price of petroleum relative to other fuels, air pollution restrictions, and lower efficiencies of this aging technology. These factors may place additional burdens on the power plants and reduce their profitability.

Figure 2 shows the nine U.S. census divisions. The Pacific region was recently divided by the EIA into two subregions—the Pacific Contiguous and Pacific Noncontiguous—for the consumption of electricity generated using petroleum liquids (see Appendix B) (EIA 2019a).

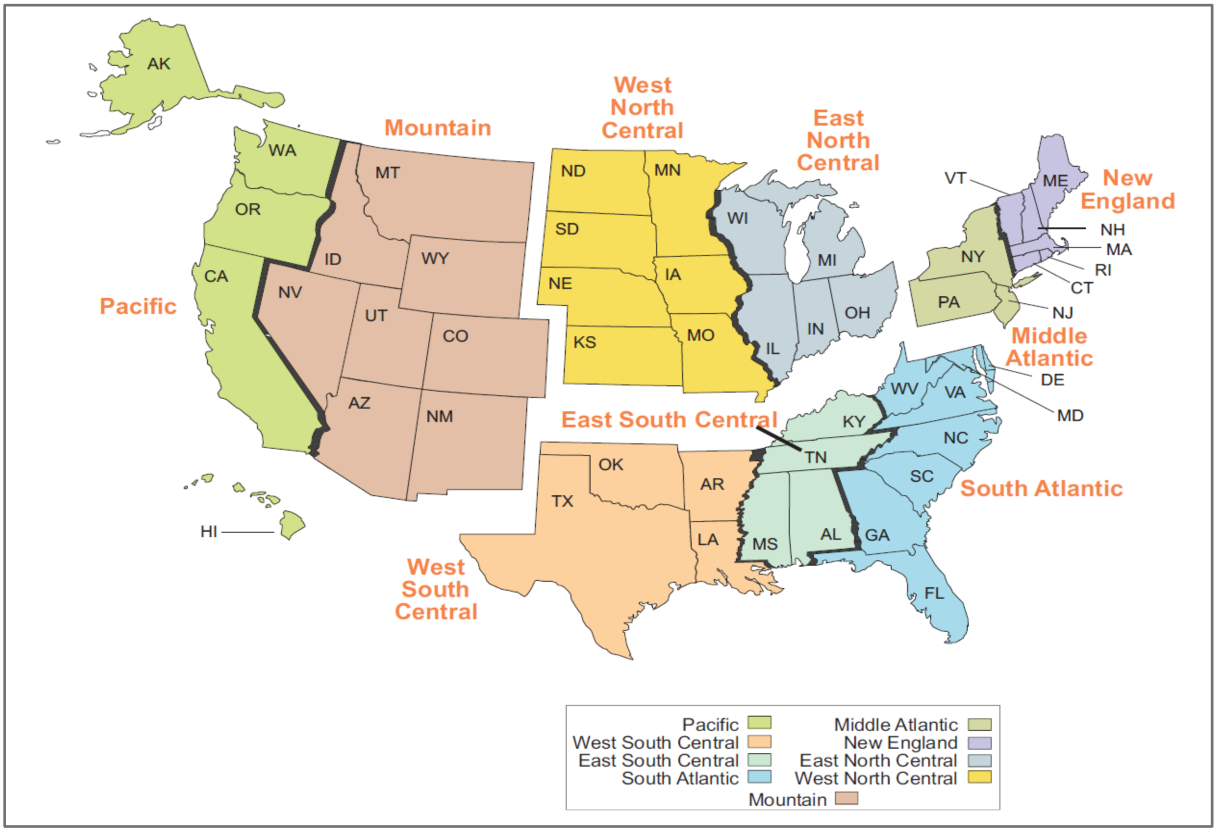

Figure 2. The Nine Census Divisions in the U.S.

Table 2 lists the petroleum-liquid consumption for electricity generation at the census division level (details in Appendix B). Figure 3 shows a plot of U.S. petroleum-liquid consumption, stocks, and receipts for power production in 2018 (EIA 2019b). This plot shows that the most substantial volumes of oil stocks are at power plants in the Pacific Noncontiguous, followed by the South Atlantic and Middle Atlantic regions. These stock inventories reflect investment decisions that account for natural gas pipeline constraints, as well as the difficulty of transporting coal to these regions. Also, while most states use petroleum-liquid supplies for peak power demands, Hawaii (PCN bar in the figure) uses petroleum for continuous power generation. It receives petroleum liquids regularly throughout the year.

Table 2. Annual Consumption of Petroleum Liquids for U.S. Electricity Generation (in thousands of barrels) for each Census Division in 2018

U.S. Census Division	Consumption (×1000 BBL)
PCC: Pacific Contiguous (California, Oregon, and Washington)	169
WSC: West South Central (Arkansas, Louisiana, Oklahoma, and Texas)	286
MTN: Mountain (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming)	366
ESC: East South Central (Alabama, Kentucky, Mississippi, and Tennessee)	603
WNC: West North Central (Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota)	625
ENC: East North Central (Illinois, Indiana, Michigan, Ohio, and Wisconsin)	1,080

U.S. Census Division	Consumption (×1000 BBL)
NE: New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont)	2,204
MAT: Middle Atlantic (New Jersey, New York, and Pennsylvania)	3,912
SAT: South Atlantic (Delaware, District of Columbia, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, and West Virginia)	5,506
PCN: Pacific Noncontiguous (Alaska, and Hawaii)	12,494
Total	**27,245**

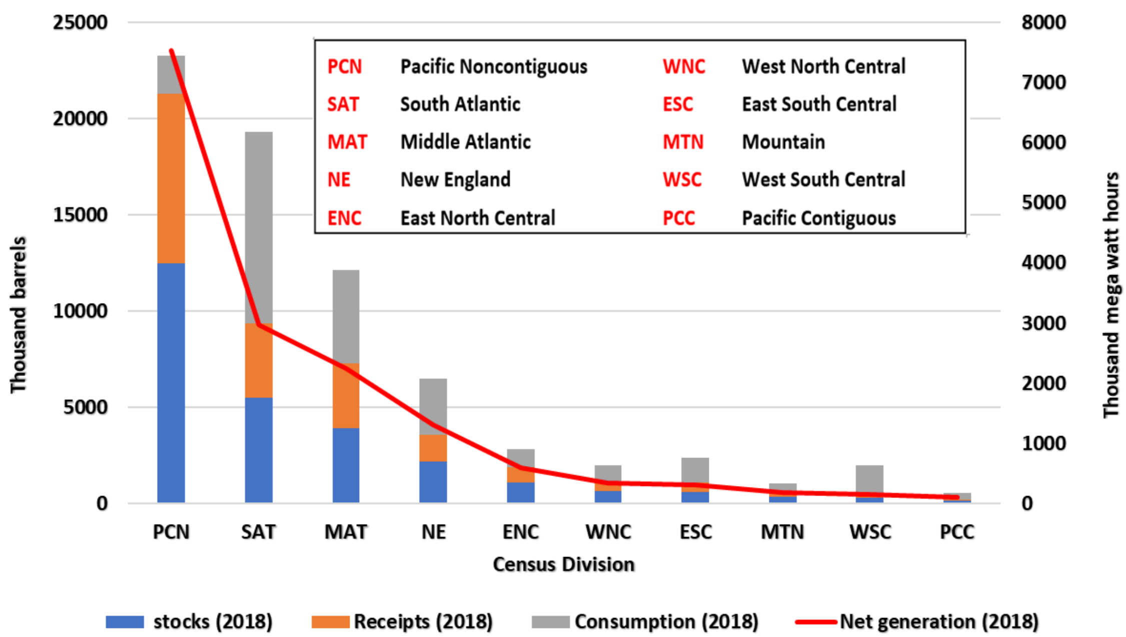

Figure 3. 2018 Consumption, Receipts, and Stocks of Petroleum Liquids for U.S. Electricity Generation by Census Division

3.0 Status of Biofuel Production

The two most likely biofuel alternatives to petroleum-liquid-based power-generation fuels are fast pyrolysis bio-oils and HTL biocrudes. Considerable work has been done on the direct combustion of bio-oil in boilers, diesel engines, and gas turbines, and there now are some commercial applications (Chiaramontia et al. 2007; Lehto et al. 2013; Fivga et al. 2019). The challenges of using raw bio-oil from pyrolysis include high water and acid contents. Since HTL is a newer technology, less information on biocrudes from that platform is available in the literature (Von Schenk and Berglin 2018). Nevertheless, Magdeldin (Magdeldin et al. 2018) worked on the integration and simulation of the HTL reactor system as part of a complete plant layout to investigate biocrude production coupled with downstream combined heat and power (CHP) production.

Bio-oil from pyrolysis can be obtained from the thermal decomposition of lignocellulosic biomass with rapid heating in the absence of oxygen, followed by rapid quenching of the vapor products.

The resulting multicomponent mixture consists of hundreds of different molecules. They are obtained from the depolymerization and fragmentation of cellulose, hemicellulose, and lignin. Bio-oil from pyrolysis is not soluble in particular petroleum or bio-based oils. This property must be taken into account when considering bio-oil for different applications (Oasmaa and Peacocke 2010). Bio-oils have been assessed as substitutes for fuel oil or diesel in many industrial boilers, furnaces, and static engines for heat and power generation. Combustion of bio-oils in decentralized applications (e.g., district heating or industrial CHP) is deemed the most promising (Xu et al. 2011; Staš et al. 2017).

HTL biocrudes have also been shown to be promising fuel oil alternatives (Von Schenk and Berglin 2018). HTL oil is produced in subcritical water conditions. It has been shown to thermally densify solid lignocellulose into liquid fuels without energy-intensive feedstock drying. Scale demonstrations have shown continuous operation with model compounds (Castello et al. 2018; Magdeldin et al. 2018). Commercial solutions have also been reported, such as Shell's HTU® (hydrothermal upgrading) process and Hydrofaction™ by Steeper Energy Aps in Denmark (Steeper Energy Aps 2018) based on a wood-to-renewable-oil concept, as shown in Table 3.(Pedersen 2016). An approximately 10 L/hour HTL process-development scale system, and bench-scale and micro-scale HTL systems are in operation at Pacific Northwest National Laboratory to process all types of biomass (terrestrial, waste, algal).

Table 3. Hydrothermal Liquefaction (HTL) Processes and Processing Conditions

Process name	Developer	Temperature [°C]	Pressure [bar]
PERC Process	Pittsburgh Energy Research Center (USA)	330–370	200
LBL Process	Lawrence Berkeley Laboratory (USA)	330–360	170–240
HTU Process	Shell Research Institute (NL)	265–350	180
STORS process	Environmental Protection Agency (USA)	300	110–150
STORS process	Organo Corp. (J.P.)	300	110–150
CatLiq Process	SCF Technologies (DK)	280–350	22.5–25
BFH Process	BFH (GER)	380	100
B/M Process Mueborit	Müller and Bothur (GER)	<220	6
Thermal Conversion Process	Changing World Technologies Inc. (USA)	200–300, 500 (two stages)	N.A.
CAT-HTR technology	Licella/Ignite Energy Resources (A.U.)	300	300
Hydrofaction	Steeper Energy (CAN/DK)	>374	>220

The HTL processes in Table 3 represent a wide range of feedstocks with a primary focus, thus far, on upgraded biocrude fuel production for the transportation sector. Use of raw HTL biocrude in internal combustion engines is limited by its requirement for hydrogenation upgrading (Ramirez et al. 2015). This upgrading step drives costs higher than what may be feasible for electricity generation applications. Some attempts have been made to use the biocrude production process to enhance the overall efficiency of power plants (Magdeldin et al. 2018).

4.0 Biofuel Applications in Heat and Power Generation

4.1 Testing and Demonstrations to Date

Some studies have recommended bio-oil as a replacement for heavy fuel oil in industrial or district heating boilers as a straightforward initial application. Co-combustion of bio-oil and petroleum-based fuel has been demonstrated (Lehto et al. 2013). In industrial-scale combustion tests, bio-oil was shown to be suitable for replacing heavy fuel oil in district heating applications (INRS 2004). However, these replacements require modifications to the combustion and emissions treatment systems. The amount of water in petroleum-based fuels is currently regulated because high levels can result in a separate corrosive phase, emulsions, or other effects on burners. The water in pyrolysis bio-oil is either dissolved or exists as a micro-emulsion so that centrifugation or other physical methods cannot eliminate (Oasmaa et al. 1997). Bio-oil water contents can be higher than 20 wt% and can, therefore, influence other fuel properties. Current burner designs are sensitive to the changes in the quality of the bio-oil, which may cause problems in the ignition, flame detection, and flame stabilization. Multi-fuel burners, pipes, and storage tanks must be constructed from corrosion-resistant material because bio-oils can be corrosive. Currently, bio-oil is being produced in commercial-size installations in Finland, The Netherlands, and Brazil for fuel and district heating applications (Staš et al. 2017).

ASTM D7544 is the specification for pyrolysis liquids produced from biomass for use in various types of fuel-burning equipment. The only commercial system in the U.S. in which bio-oil is used for heat generation is located at the Red Arrow Products pyrolysis plant in Wisconsin, which has been operating for ten years. Ensyn built 13 licensed facilities for Red Arrow, five of which are still in operation today (Ensyn 2017). The largest is a 2 × 200 metric ton per day plant in Quebec. In Finland, Fortum Power and Heat’s 1.5 MW district heating plant in Masala has burned bio-oil since 2010 (Bradley 2006; Lehto et al. 2013). The bio-oil was produced at Metso’s pilot plant and was entirely oil, including an extractive-rich top phase. No chemical solvents or additives were used. The existing burner was replaced with a new bio-oil burner consisting of a modified monoblock heavy fuel oil burner initially designed for high-pressure atomization.

Green Fuel Nordic (GFN) in Finland created an investment road map for using fast pyrolysis technology to produce second-generation bio-oil from forest-based feedstocks. Envergent Technologies LLC, a Honeywell company, signed a memorandum of understanding with GFN by which the two companies would collaborate on projects to convert biomass to renewable fuel for use in district heating systems in Finland. The companies evaluate the installation of new facilities to convert forest residues into liquid biofuel using Envergent’s Rapid Thermal Processing (RTP™) technology. The liquid biofuel may be used in industrial burners for heat, replacing petroleum-based fuel.

For decades, the only commercial option available to produce electricity from wood, wood residues, and other solid biomass has been direct combustion coupled to a steam turbine in a Rankine cycle. The most apparent substitution for biofuels in existing power-generation systems is for oil-fired and natural-gas-fired plants(Bradley 2006). Brammer reported on the use of bio-oil in heat, power, or CHP in 14 European countries (Brammer et al. 2006; Yang et al. 2017).

Bio-oil produced by Red Arrow Products Company via the RTP™ process was co-fired in a coal station at the Manitowoc Public Utilities power station, Wisconsin, in a 20 MWe, low-sulfur, Kentucky coal-fired stoker boiler. A total of 370 hours of operation were achieved, feeding 5% of thermal input by pyrolysis oil, corresponding to 1 MWe of power output. The plant was operated without significant problems after cost-effective modification of the boiler to allow for co-firing.

A few companies are currently commercializing bio-oil for energy applications. Ensyn/Envergent Technologies, Forschungszentrum Karlsruhe (KIT), Biomass Technology Group B.V. (BTG), and Fortum, together with Metso and GFN, have the most advanced technologies (see details in Appendix C). Published results showed that bio-oil was not suitable for a conventional diesel engine and produced many problems because of specific properties (Xu et al. 2011). For example, bio-oils typically cannot auto-ignite without additives (e.g., nitrated alcohol), and need a pilot injection system. The amount of coke formed during the combustion of bio-oil, which clogs fuel injectors, is another issue.

Bio-oil combustion has been demonstrated in a 2.5 MWe industrial gas turbine (Xu et al. 2011). Here, the J69 combustion system consists of an annular combustor and a centrifugal fuel injector rotating at the shaft speed. Bio-oil was also co-fired in a 350 MWe natural-gas-fired power station in Harculo, The Netherlands, by BTG, where 15 tons of bio-oil (>1% bio-oil in the feed) was co-fired with minimal retrofitting and high system reliability. Here, bio-oil was converted into 25 MWh of electricity (Venderbosch et al. 2002). In general, biofuel applications that generate heat appear to be the most economically competitive, followed by CHP (Mohan et al. 2006).

4.2 Power Plant Derating Estimates with Biofuels

Biocrude and bio-oil have lower energy densities than petroleum liquids. Thus, when firing in a boiler in sufficient quantities, the derating of the boiler performance is likely. One example, prepared for the New Hampshire Office of Energy, evaluates the economic viability of locating a bio-oil facility with associated derating (Stewart 2004). Here, a biorefinery with a capacity of 100 tons per day is estimated to generate 4.8 million gallons of bio-oil with the heating equivalent of 2.64 million gallons of #2 fuel oil. The heat content of bio-oil (75,500 BTU per gallon) is only 55% that of #2 fuel oil. Therefore, 1.82 gallons of bio-oil is required to obtain the same amount of heat released when burning one gallon of #2 fuel oil. This higher required flow rate of bio-oil leads to changes in spray characteristics, such as the atomizing quality, and potentially necessitates modifications to the nozzle and combustion chamber design (Shaddix and Hardesty 1999; Tzanetakis et al. 2010).

The energy content in the air-fuel mixture also influences the output of the engine (Dasappa 2001). Depending upon the heating value and the stoichiometric air requirement, the energy content in the engine determines the power developed by the generator. For designing a specific combustion chamber, technical studies assume that the effects of ignition time, ignition quality, and mixture control should be standardized at sea level for both original and alternative fuels. The heating values and bio-oil and biocrude yields used in power-generation calculations are listed in Table 4. Bio-oil has a 48% lower heat content than heavy fuel oil. The derating factor expresses only the additional energy needed to accomplish the same power generation. The method of calculation based on the heating values is illustrated in Appendix D for a New England example.

Table 4. Bio-Oil and Biocrude Heating Values and Conversion Yields

Parameter	Value	Reference
The heating value of petroleum-based heavy fuel oil (LHV[a], M.J./kg)	40.6	(Hou et al. 2016)
The heating value of pyrolysis oil (LHV, M.J./kg)	21.2	(Lucchesi and Maschio 1984)
The heating value of wood HTL biocrude (LHV, M.J./kg)	25.5	(Magdeldin et al. 2018)
Conversion yield of fast pyrolysis bio-oil from forest residues (wt%)	51%	(Oasmaa et al. 2010)
Conversion yield of fast pyrolysis bio-oil from pine wood (wt%)	64%	(Oasmaa et al. 2010)
Conversion yield of fast pyrolysis bio-oil from corn stover (wt%)	56%	(Agblevor et al. 1995)
Conversion yield of HTL biocrude from forest residues (wt%)	37%	(Nie and Bi 2018)
Conversion yield of HTL biocrude from pine wood (wt%)	29%	(Zhu et al. 2014)
Conversion yield of HTL biocrude from corn stover (wt%)	25%	(Collett et al. 2019)

a. LHV = lower heating value

Because of their lower heating values, bio-oils must be fired at higher flow rates than heavy oils to achieve the same heat output. However, the higher oxygen contents of bio-oils allow their combustion air/fuel ratios to be about half those needed for heavy oils. The net effect is similar to adiabatic flame temperatures of bio-oils compared to heavy oil (Lehto et al. 2013).

The physical and chemical properties of bio-oils are high water and oxygen content, high viscosity and surface tension, wide volatility distribution, and char content. These properties can negatively affect atomization quality, ignition, and droplet vaporization. They can also change the burning rate, clogging, coking tendency, and emissions in combustion systems.

5.0 Feedstock Availability Estimates for Power-Generation Biofuels

5.1 Modeling Approach

To assess feedstock supply and cost, feedstock supply was modeled in two stages. First, potential county-level farmgate feedstock supplies (i.e., supplies available including all costs up to the farmgate but before transportation and logistics costs) as a function of price are quantified at the farmgate using the Policy Analysis System (POLYSYS) model. Next, these county-level supplies are allocated to a network of hypothetical biorefinery locations using the Supply Characterization Model (DOE 2016).

POLYSYS is a partial-equilibrium model used to simulate potential supply and price response to market changes in the U.S. agricultural sector (De La Torre Ugarte and Ray 2000). Significant inputs to the model include land area, crop yields (both conventional and energy crops), and crop production. POLYSYS is used to quantify how farmers could respond to future demands for feedstock. To determine county-level farmgate feedstock supplies as a function of the price for each scenario, potential supplies were simulated in $5 increments, with farmgate prices ranging from $30 to $80 per dry ton. To reflect a range of county-level farmgate supplies at varying prices, we developed county-level supply curves by calculating marginal supplies (i.e., the difference in the quantity of supplies at each farmgate price step) at each price increment for each county. In this analysis, costs include harvest operations plus a specified profit ($5, $10, or $15 per dry ton). Detailed assumptions of a recent application of POLYSYS are described in Appendix C of the 2016 Billion-Ton Report (BT16), (DOE 2016). Farmgate (i.e., roadside, before transportation) supplies of logging residues and forestry whole trees derived from the Forest Sustainability and Economic Assessment Model (ForSEAM), as described in Chapter 3 of the BT16 (DOE 2016), are derived from the Bioenergy Knowledge Discovery Framework (bioenergykdf.net).

Next, the Supply Characterization Model was used to allocate the county-level farmgate supplies to hypothetical biorefineries. The model also used to add the associated transportation cost for each county-level farmgate feedstock supply to each biorefinery. Delivered supply is modeled for facilities with capacities of 100, 500, and 1,000 dry tonnes per day. Logistics assumptions are the same as described in Chapter 6 of the BT16 (DOE 2016). The farmgate supplies are allocated to sub-county distribution by following the U S. Department of Agriculture Cropland Data Layer (USDA 2019). This analysis is simulated for the conterminous 48 states for all feedstock options. Feedstock prices are reported here as biorefinery-specific, weighted-average prices in 2014 dollars.

5.1 Feedstocks Price Estimates

The farmgate cost of the biomass and the transportation cost to the hypothetical biorefineries in each region were next estimated. Valuation of feedstock costs is based on the dry biomass needed to replace petroleum liquids used in power generation for each region. Clean wood (whole trees), forest residues, and corn stover were evaluated. The feedstocks were selected to reflect materials commonly grown and available in 10 census divisions (see Appendix E). Some fertile regions of specific biomass types are far from the concentrated power-generation areas (like the East coast in the U.S). The resulting estimates are shown in Appendix E. Figures 4 to 6 show the respective price-supply curves for each of the feedstocks, for each of the U.S. census division. Process facilities were assumed to have 100-tonne-per-day capacities for each of these estimates.

Figure 4 shows relatively stable pricing estimates for the high corn-stover-producing regions (West North Central and East North Central), while prices escalate with demand in other regions. For both the forest residues and whole trees (Figure 5 and Figure 6), prices are predicted to escalate at certain demand levels, with escalation at the most abundant level in the South Atlantic region. Figure 7 shows price-supply curves for all three feedstocks for one U.S. region and three different processing facility scales. This plot shows the minimal effect of facility size on the pricing estimates.

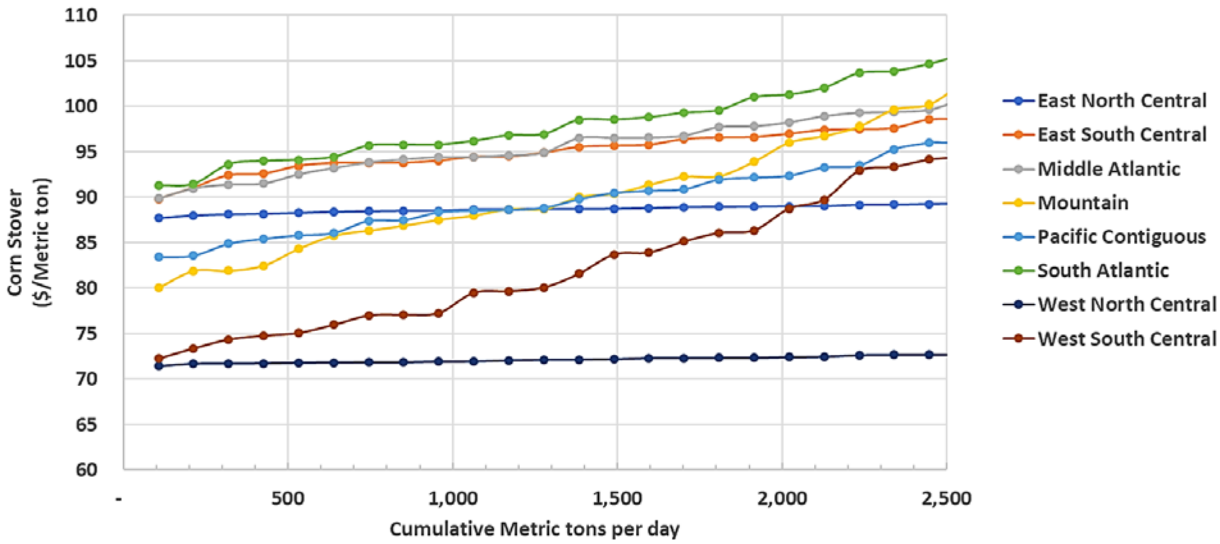

Figure 4. Price-Supply Curves for Corn Stover (assumes 100-tonne-per-day facilities)

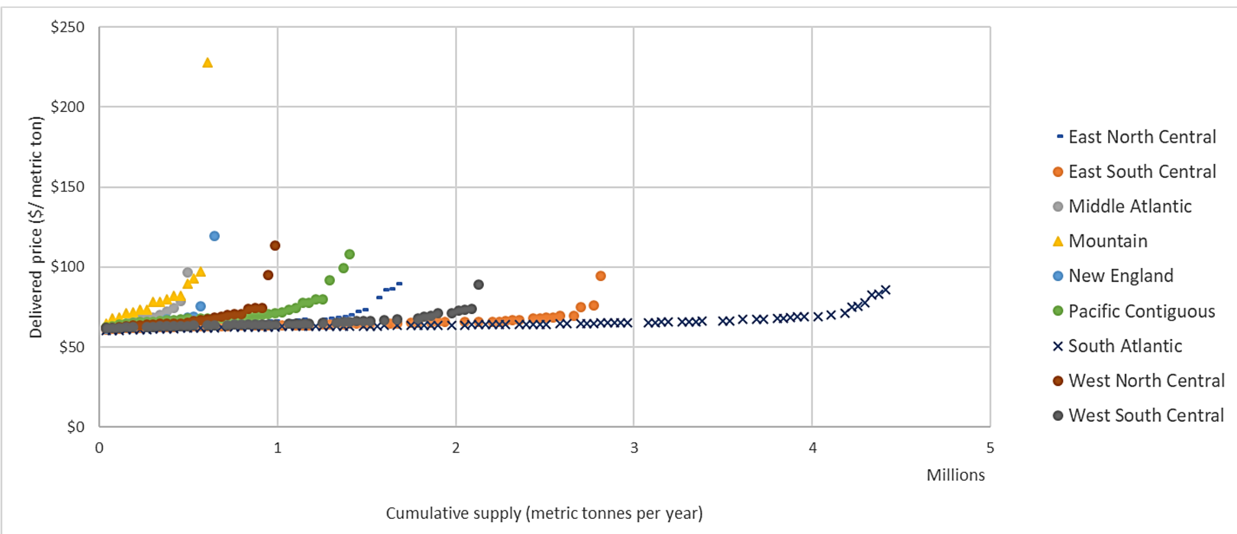

Figure 5. Price-Supply Curves for Forest Residues (assumes 100-tonne-per-day facilities)

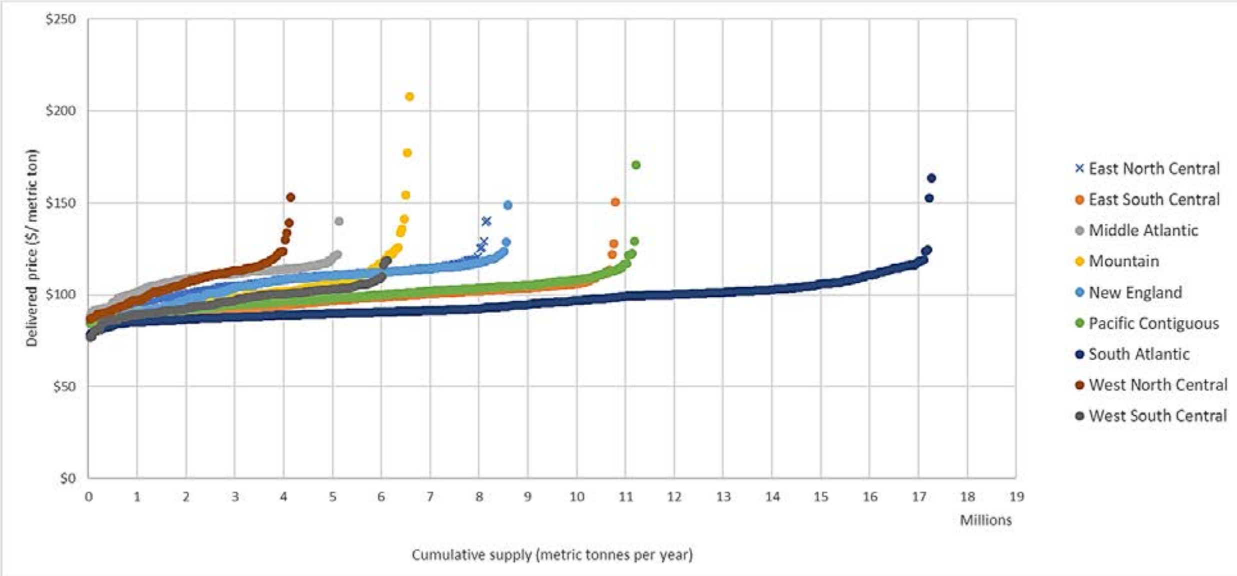

Figure 6. Price-Supply Curves for Whole Trees (assumes 100-tonne-per-day facilities)

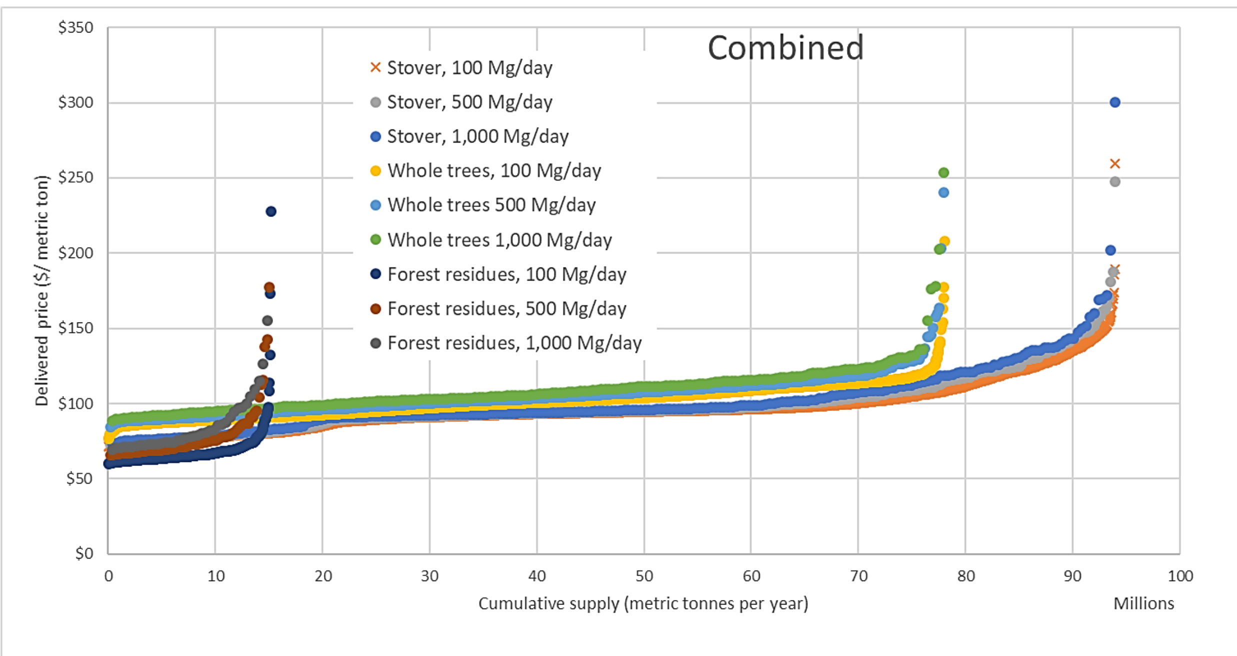

Figure 7. Price-Supply Curves for Three Types of Biomass and for Three Biorefinery Sizes

5.2 Regional Feedstock Availability Estimates

Each feedstock was next analyzed, assuming that it alone provided the full quantity required for power plants, in isolation from other biomass sources. Table 5 shows the estimates of total U.S. feedstocks along with the approximate number of corresponding biorefineries that would be required based on simple conversions of each biomass type into bio-oil or biocrude at equivalent total heating values.

Table 5. Number of Biorefineries Needed to Support Existing U.S. Petroleum-Fired Electricity Infrastructure

	Bio-oil			Biocrude		
Feedstock (all dry)	Clean Wood	Forest Residues	Corn Stover	Clean Wood	Forest Residues	Corn Stover
Total annual U.S. feedstock needed (millions of dry tonnes)	18	23	21	31	24	36
Number of plants needed (@ 2,000 dry tonnes/day each)	25	32	29	42	34	49
Number of plants needed (@ 1,000 dry tonnes/day each)	51	64	57	84	67	98
Number of plants needed (@ 500 dry tonnes/day each)	101	128	115	167	134	197
Number of plants needed (@ 100 dry tonnes/day each)	505	640	574	837	671	985

Many power-generation units are co-located, where they have a direct effect on electricity consumption and are not necessarily close to a preferred biorefinery location. The strategic interactions among regions and plants, specifically biorefineries situated at boundaries of the highly biomass-productive area, are beyond this study. These links require a specialized tool, such as the “BioTrans” model developed at the Energy Research Centre in the Netherlands, which is a long-term planning tool that explains the interactions among regions and between oil and biofuels, and also examines the system’s resilience in supply/demand shocks (Lensink et al. 2007; Uría-Martínez and Leiby 2012).

Next, the feedstock availabilities were estimated for each of the U.S. census divisions. To perform these estimates, the feedstock price was varied to estimate the effects of supply variation, as described in the previous section. Table 6, Table 7, and Table 8 represent the regional availability of clean wood, forest residues, and corn stover in each census division as a function of price. The prices indexed in these tables are approximate and exclude processing and transportation costs, and they do not reflect the accuracy required to supply feedstocks to biorefineries. Alaska and Hawaii are not included in the table data because information for those states is incomplete. Alaska does not have state-of-the-forest inventory data, and Hawaii is only now beginning to carry out an island-wide forest inventory (DOE 2016).

Table 6. Availability Estimates for Clean Wood as a Function of Cost

	Estimated availability (millions of tonnes/yr)						
Feedstock Price ($/dry tonne)	40	50	60	70	80	90	100
East North Central		1.8	3.9	9.6	9.6	9.6	9.6
East South Central	0.2	5.9	13.1	13.1	13.1	13.1	13.1
Middle Atlantic		0.8	1.9	6.6	6.6	6.6	6.6
Mountain		3.5	7.2	7.7	7.7	7.7	7.7
New England		2.4	4.0	10.6	10.6	10.6	10.6
Pacific Contiguous		5.1	13.6	13.8	13.8	13.8	13.8
South Atlantic	0.7	12.4	20.8	22.5	22.5	22.5	22.5
West North Central		1.5	2.8	5.1	5.1	5.1	5.1
West South Central	0.6	3.5	8.4	8.4	8.4	8.4	8.4

Table 7. Availability Estimates for Forest Residues as a Function of Cost

	Estimated availability (millions of tonnes/yr)						
Feedstock Price ($/dry tonne)	40	50	60	70	80	90	100
East North Central	2.0	2.0	2.0	2.0	2.0	2.0	2.0
East South Central	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Middle Atlantic	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Mountain	0.7	0.7	0.7	0.7	0.7	0.7	0.7
New England	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Pacific Contiguous	1.7	1.7	1.7	1.7	1.7	1.7	1.7
South Atlantic	5.3	5.3	5.3	5.3	5.3	5.3	5.3
West North Central	1.3	1.3	1.3	1.3	1.3	1.3	1.3
West South Central	2.6	2.6	2.6	2.6	2.6	2.6	2.6

Table 8. Availability Estimates for Corn Stover as a Function of Cost

	Estimated availability (millions of tonnes/yr)						
Feedstock Price ($/dry tonne)	40	50	60	70	80	90	100
East North Central		20.5	25.6	28.1	30.0	31.0	31.6
East South Central		0.8	1.9	2.1	2.1	2.1	2.2
Middle Atlantic		0.8	1.6	1.7	1.8	1.9	1.9
Mountain		0.8	1.1	1.2	1.2	1.4	1.4
New England							
Pacific Contiguous	0.1	1.1	1.2	1.2	1.2	1.2	1.2
South Atlantic		0.7	1.4	1.5	1.5	1.5	1.5
West North Central	24.6	53.5	61.0	63.6	67.2	68.7	69.9
West South Central	0.9	1.4	2.0	2.2	2.2	2.3	2.3

Using the feedstock price and supply data, the average price of each feedstock was estimated for each of the census divisions, based on the amounts needed to offset current petroleum-liquid-based electricity generation. These estimates are shown in Table 9 for bio-oil and biocrude. Detailed costing is given in Appendix F.

Table 9. Average Estimated Feedstock Pricing for the Supply of Bio-Oil and Biocrude to Each U.S. Census Division. 100 dry tonne/day capacity bioprocessing facility size assumed.

	Corn Stover Price ($/dry tonne)		Forest Residues Price ($/dry tonne)		Clean Wood Price ($/dry tonne)	
	Bio-Oil	Biocrude	Bio-Oil	Biocrude	Bio-Oil	Biocrude
New England	N/A	N/A	70	70	89	93
Middle Atlantic	105	105	71	71	103	107
East North Central	89	92	65	65	90	92
West North Central	72	72	64	64	89	91
South Atlantic	105	105	65	65	86	88
East South Central	93	95	62	62	85	86

West South Central	74	76	62	62	79	81
Mountain	84	86	72	72	87	87
Pacific Contiguous	85	85	64	64	85	85

The data in Table 9 indicate that a conservative price range for each feedstock is $80–$84/dry tonne. Using a value of $80, estimates of biomass availability were revised. These estimates are shown in Figure 8 for each biomass type. Overlaid on these data (dashed bars) are the corresponding estimates of how much of each biomass type would be required to supply the current petroleum-liquid power-generation plants in that region. HTL biocrude processing was also assumed because the overall biomass required for the HTL process is higher than that for pyrolysis-based bio-oil (1.1 to 1.7 times, depending on the feedstock).

The data in Figure 8 show that the petroleum-liquid power generation in each of the census divisions could be supplied by one or more of the feedstocks evaluated. For all regions, clean wood supplies alone could provide ample supply. For all but two regions (Middle Atlantic and New England), forest residues alone could provide enough supply. Finally, for all regions but three (Middle Atlantic, New England, and South Atlantic), corn stover alone could provide enough supply.

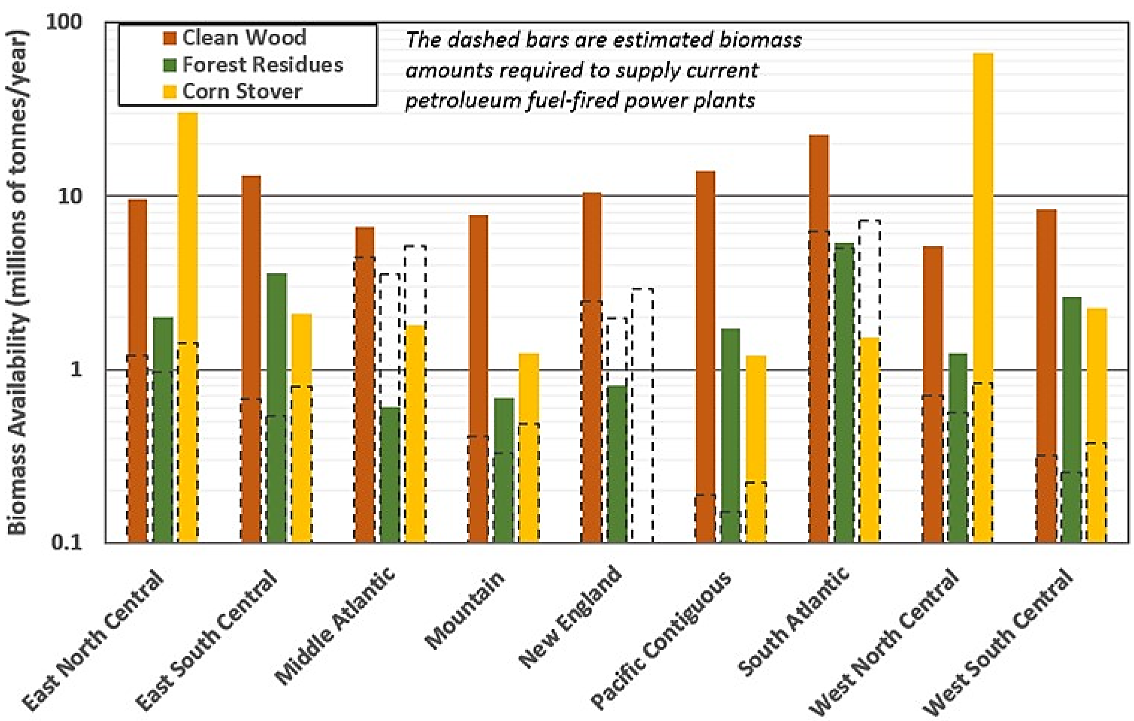

Figure 8. Biomass Availability for U.S. Census Divisions, along with Required Amounts for Each Respective Region's Petroleum Fuel-Fired Power Plants (dashed bars). An $80/dry tonne feedstock price was used for the availability estimates.

6.0 Minimum Fuel Selling Price (MFSP) Estimates

The MFSP biofuels were derived from techno-economic analysis models. The critical assumptions used in these estimates include biomass cost, plant capacity, and reactor technology (Wright et al. 2010a). The biomass feedstock price, described in previous sections, includes harvesting and assembly costs in warehouses and transportation costs from the field to the biorefinery gate. Based on the prior estimates, a price of $84 per dry tonne was used for each feedstock in the subsequent fuel processing estimates. Table 10 shows the results of the MFSP estimates for each census division and feedstock type. Here, a 100 dry tonne/day capacity was assumed. These data show that bio-oil prices in all census divisions are lower than current heating oil prices (by approximately 14%). However, in all cases, biocrude price predictions are more than double the current wholesale oil prices, primarily due to the conversion yields and other operating cost differences. Recall that the corn stover and forest residues are scarcest in the South Atlantic, Middle Atlantic, and New England regions. In other words, they could not fully support all biorefineries in these areas.

Table 10. Predicted MFSP for Each U.S. Census Division. A biorefinery capacity of 100 dry tonnes/day was assumed in all cases.

	Predicted Minimum Fuel Selling Price ($/gallon)						Average Wholesale Heating Oil Price (March 2019)
	Bio-oil			**Biocrude**			
	Corn Stover	Forest Residue	Clean Wood	Corn Stover	Forest Residue	Clean Wood	
West North Central	1.76	1.71	1.86	4.65	4.56	4.87	2.09
West South Central	1.77	1.70	1.80	4.70	4.54	4.75	2.09
Mountain	1.83	1.76	1.85	4.81	4.65	4.82	2.09
Pacific Contiguous	1.84	1.71	1.83	4.80	4.55	4.80	2.09
East North Central	1.86	1.71	1.86	4.88	4.57	4.88	2.09
East South Central	1.88	1.70	1.84	4.92	4.54	4.81	2.09
South Atlantic	1.96	1.72	1.84	5.03	4.57	4.83	2.09
Middle Atlantic	1.96	1.75	1.95	5.03	4.63	5.06	2.09
New England	--	1.75	1.86	--	4.62	4.89	2.09
Average ± Std. Dev	1.82 ± 0.07	1.72 ± 0.02	1.84 ± 0.04	4.79 ± 0.14	4.57 ± 0.04	4.82 ± 0.09	2.09

Figure 9 shows the estimated cost for produced bio-oil and biocrude relative to biorefinery capacity. Here, capacities of 100, 500, 1,000, and 2,000 dry tonnes/day of clean wood are shown. This plot shows the most significant decrease in cost with an initial capacity increase from 100 to 500 tonne/day.

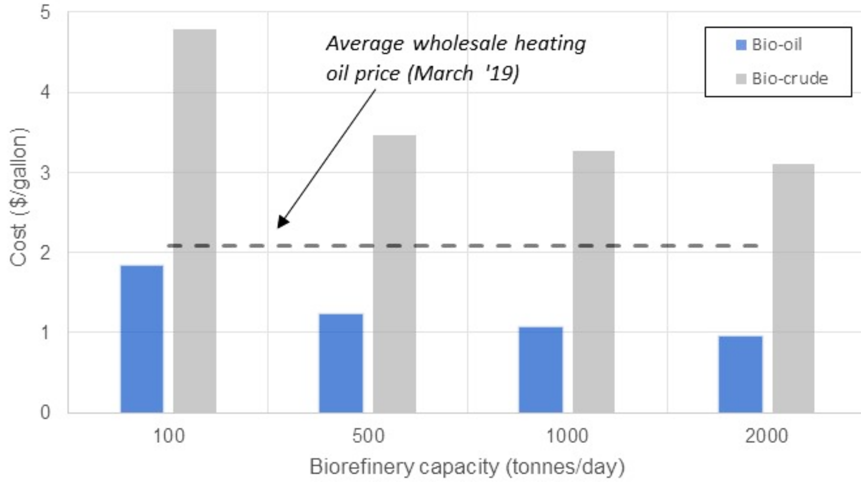

Figure 9. Estimated Biofuel Costs Relative to Refinery Capacities. Clean wood feedstock assumed at $84/dry tonne.

7.0 Conclusions

The key conclusions of this study are the following:

- The U.S. consumption of petroleum liquids for electricity generation was 27 million barrels in 2018, with a corresponding cost of $2.4 billion.
- Both bio-oil from pyrolysis and biocrude from HTL were evaluated as potential biofuel replacements for petroleum liquids currently used in U.S. power production. Enough clean wood is available to supply the expected need for biorefineries as a sole feedstock in all regions. Corn stover and forest residues were determined to be available in most U.S. regions as sole feedstock candidates, but not in the eastern coastal regions (New England, Middle Atlantic, and South Atlantic).
- For quantities that could offset current petroleum liquids used in U.S. power production, the biomass source feedstock costs for corn stover, clean wood, and forest residues are estimated to range between $60 and $100 per dry metric tonne in most U.S. census division.
- The number of current research and industrial processes for bio-oil production in Europe and North America is growing, and the interest in commercial applications is increasing.
- The MFSPs of bio-oil and biocrude were estimated for each feedstock type and census division. This analysis showed fast pyrolysis bio-oil projections to be lower (14% on average) than current wholesale petroleum-based heating oil prices in each of the regions, assuming 100 dry tonnes/day processing capacity. However, HTL biocrude predictions were significantly higher (double) in all cases. The most significant decreases in MFSP resulted from an initial biorefinery capacity increase from 100 to 500 tonne/day. Note that the current high biocrude price estimates should not deter research into cheaper production methods from affordable biomass sources, especially since the biocrude specifications closely aligned with those for petroleum liquids.
- The preliminary results of this study indicate that biofuels could be an economical alternative to current petroleum liquids in U.S. power generation. However, future research is needed to determine the necessary biofuel characteristics to support current generation equipment.

Both power generation and biofuel production stakeholders should be engaged to outline the research and testing needed to identify the technical hurdles toward the opportunity.

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Appendix A – Net Electricity Generation per Electricity Sector (EIA 2017)

Energy Source	Billion kWh	Share of Total
Total - all sources	4,178	
Fossil fuels (total)	2,651	63.50%
Natural gas	1,468	35.10%
Coal	1,146	27.40%
Petroleum (total)	25	0.60%
Petroleum liquids	16	0.40%
Petroleum coke	9	0.20%
Other gases	12	0.30%
Nuclear	807	19.30%
Renewables (total)	713	17.10%
Hydropower	292	7.00%
Wind	275	6.60%
Biomass (total)	63	1.50%
Wood	41	1.00%
Landfill gas	11	0.30%
Municipal solid waste (biogenic)	7	0.20%
Biomass waste (other)	3	0.10%
Solar (total)	67	1.60%
Photovoltaic	63	1.50%
Solar thermal	4	0.10%
Geothermal	17	0.40%
Pumped storage hydropower	−6	−0.10%
Other sources	13	0.30%

Appendix B – Petroleum-Liquid Consumption for Electricity Generation (thousands of barrels)

Census Division	State	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
U.S.	Total	53,846	43,562	40,103	27,326	22,604	23,231	31,531	28,925	22,405	21,696	27,245
		5,593	3,125	2,062	1,267	891	2,017	3,673	3,440	1,157	1,362	2,204
	Connecticut	990	593	842	369	259	555	908	737	209	345	637
	Maine	661	629	500	320	218	461	526	927	227	272	331
	Massachusetts	3,628	1,525	548	361	304	713	1,646	1,325	598	479	804
	New Hampshire	258	333	135	143	58	187	454	291	67	163	304
	Rhode Island	44	37	25	28	31	75	113	151	44	81	NM
New England	Vermont	12	7	12	46	22	27	26	8	12	22	NM
	Total	8,140	6,106	4,257	2,823	1,720	2,559	5,484	4,680	1,888	1,693	3,912
	New Jersey	631	485	417	233	77	187	786	496	130	126	407
	New York	6,112	4,245	2,688	1,672	1,053	1,705	3,423	3,101	1,142	1,018	2,488
Middle Atlantic	Pennsylvania	1,397	1,377	1,152	918	590	667	1,275	1,083	616	549	1,017
	Total	1,859	1,505	1,515	1,519	1,262	1,190	1,478	1,106	1,083	996	1,080
	Illinois	272	230	205	161	137	136	168	107	135	104	143
	Indiana	322	266	276	310	217	257	298	287	204	216	234
	Michigan	552	422	395	374	281	259	285	222	248	227	245
	Ohio	530	491	552	589	526	466	598	422	426	377	401
East North Central	Wisconsin	183	97	87	85	100	72	129	67	71	73	57
	Total	817	656	731	639	634	684	787	590	546	552	625
	Iowa	180	128	183	158	204	184	128	95	161	118	121
	Kansas	91	86	98	86	78	109	116	110	66	121	NM
	Minnesota	191	134	68	56	62	75	143	69	67	76	85
	Missouri	142	156	236	165	163	136	224	209	165	136	193
	Nebraska	73	45	57	70	43	94	99	16	16	16	18
	North Dakota	89	83	71	83	66	65	54	53	60	70	75
West North Central	South Dakota	50	24	18	21	18	21	23	38	11	15	15

Census Division	State	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	Total	19,529	15,040	15,278	5,304	3,416	3,046	6,627	5,463	4,010	3,270	5,506
	Delaware	379	482	103	75	46	43	300	255	114	50	247
	District of Columbia	163	85	434	275	26	-	-	-	5	-	-
	Florida	14,767	10,637	10,431	2,441	1,262	866	938	1,100	1,428	926	1,020
	Georgia	343	275	267	233	232	172	497	284	209	239	389
	Maryland	791	624	659	467	409	544	1,105	484	353	243	517
	North Carolina	553	537	566	406	352	401	895	801	485	486	977
	South Carolina	249	290	315	213	216	208	500	385	214	202	464
	Virginia	2,041	1,802	2,232	867	624	542	2,109	1,907	987	916	1,603
South Atlantic	West Virginia	242	308	272	327	250	270	284	247	216	208	290
	Total	1,088	967	1,079	927	757	650	832	691	560	521	603
	Alabama	281	296	306	228	198	143	206	153	79	64	148
	Kentucky	255	281	230	256	232	227	246	244	211	189	177
	Mississippi	154	38	141	68	29	25	31	31	34	25	54
East South Central	Tennessee	397	352	402	374	297	255	349	264	237	243	225
	Total	903	639	548	494	415	369	366	463	293	298	286
	Arkansas	105	149	78	96	56	73	49	108	76	85	61
	Louisiana	560	232	213	97	73	95	91	125	30	44	NM
	Oklahoma	31	26	25	31	22	19	22	20	32	29	33
West South Central	Texas	206	232	232	271	264	182	203	211	155	140	107
	Total	465	452	503	488	433	406	474	424	428	409	366
	Arizona	92	117	121	98	77	81	108	92	98	107	96
	Colorado	45	33	50	56	31	29	38	24	21	23	30
	Idaho	-	-	-	-	-	-	-	-	-	-	-
	Montana	40	30	29	38	31	33	55	32	38	31	37
	Nevada	28	32	25	28	41	35	29	31	22	19	21
	New Mexico	102	85	92	72	88	110	124	126	101	81	41
	Utah	78	63	81	88	71	46	43	34	55	66	62
Mountain	Wyoming	80	91	104	107	95	73	77	85	94	83	78

Census Division	State	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	Total	390	335	172	163	166	159	161	213	190	150	169
	California	299	241	115	88	97	95	100	164	149	94	121
	Oregon	25	9	6	13	12	11	18	11	8	18	NM
Pacific Contiguous	Washington	67	84	51	62	57	52	44	38	32	38	40
	Total	15,062	14,736	13,957	13,703	12,910	12,151	11,650	11,856	12,250	12,444	12,494
	Alaska	1,655	1,996	1,622	1,613	1,710	1,386	1,261	1,346	1,454	1,585	1,391
Pacific Noncontiguous	Hawaii	13,407	12,740	12,335	12,090	11,200	10,765	10,388	10,510	10,797	10,859	11,103

Appendix C – Biofuels in Biopower Review

Company	Country	Process	Scale	Type	Remarks	References
Envergent (UDP)	USA, Canada	RTP- heating plant	Demo/ commercial	Fast pyrolysis	An industrial plant in Quebec, Canada. Start-up 2018. Pyrolysis oil is used as heating oil. Production about 50,000 t/year	
Valmet (Fortum)	Finland	Power plant	Demo/ commercial	Fast pyrolysis	Commercial plant in Finland in operation since 2013. Pyrolysis oil is used in the power plant in Espoo. Production about 50,000 t/year. Initiated collaboration with Preem in 2018 to look at possible integration into the oil refinery.	(Von Schenk and Berglin 2018)
Steeper Energy	Denmark, Canada	Hydrofaction	Pilot	HTL (supercritical)	Building a demo plant in Norway together with Silva Green Fuel (a joint venture between Statkraft and Sodra). Planned start-up 2019, production capacity 4,000 L bio-oil/ d.	
BTG	Netherlands	polygeneration pyrolysis plant	25 MW(th)	Fast pyrolysis	Demo/commercial plant in the Netherlands in operation since 2015. Pyrolysis oil is used as heating oil. Production about 25,000 t/year. BTG BioLiquids B.V. (BTG-BTL) is a subsidiary company of BTG and was established to commercialize the fast pyrolysis technology as developed by BTG to produce electricity process steam. The installation owned and operated by the company Empyro BV, a joint venture of BTG Bioliquids and Tree Power B.V. The plant is built in Hengelo, the Netherlands, on the premises of Akzo-Nobel. BTG modified two compression-ignition engines to develop this application, viz. a one-cylinder and a four-cylinder prototype, which can be seen as a prototype for a commercial-size CHP system.	(Van de Beld et al. 2013)
PyTec	Germany	diesel engine	450 kWe		PyTec use of fast pyrolysis oil in diesel engines. On average, 120 L/h of bio-oil were consumed, achieving an electrical output of 305 kWe and a reduction in exhaust gas temperature of 150°C compared to diesel combustion.	
Wärtsilä	Finland	diesel engine	1.5 MW and 200 MW	Bio-oil	The Marseglia Group is the first producer in the world to use liquid biomass with internal combustion engines. Two power plants are located on the coastline near the city of Bari in the region of Puglia: the BL2 plant is in Monopoli, south of Bari, and the BL3 plant is in Molfetta, north of Bari. Both plants are equipped with Wärtsilä 18V46 engines producing 153 MW in total. The first work on using pyrolysis liquid in diesel engines was carried out in Finland by the Technical Research Centre of Finland (VTT) and Wärtsilä. It showed that bio-oil could be efficiently used in pilot-ignited medium-speed diesel engines. The most essential identified problems were difficulties in adjusting the injection system	(Wärtsilä 2014)
VTT	Finland	Heating plant	1.5 MW	Bio-oil	Metso, Fortum, UPM, and VTT have been developing an integrated bio-oil production concept. Diesel engines have been tested. Around 40 tons of the bio-oil produced have been combusted in Fortum's 1.5 MW district heating plant in Masala, Finland, with high efficiency. Fortum is investing in the commercialization of integrated fast pyrolysis technology connected to the Joensuu CHP production plant in Finland, a concept delivered by Metso Power.	(Chiaramonti a et al. 2007)
OPRA Turbines	Netherlands	Gas turbines	75 kW		Gas turbines running on pyrolysis bio-oils have been developed. This application has not been commercialized yet. OPRA Turbines continues pushing limits through innovation. OPRA is participating in the EnCat project (Enhanced catalytic fast pyrolysis of biomass for maximum production of high-quality biofuels).	(Staš et al. 2017)

Company	Country	Process	Scale	Type	Remarks	References
Ensyn	Canada, U.S.				Envergent Technologies and Ensyn's RTP technology produces a high yield of liquid fuel from solid biomass. It can be used in an advanced cycle for high-efficiency production of electricity. The advanced cycle can then be coupled to a steam turbine (or another heat engine) in a combined cycle to utilize waste heat for maximum power production. RTP pyrolysis oil can be used to fuel advanced cycle power producers, including a diesel engine generator set (GenSet) and a power turbine GenSet.	(Staš et al. 2017)
ZSW	Germany	Stirling engine	25 kW	Bio-oil	ZSW fueled a 25 kW Stirling engine with a modified oxidative burner with air atomization. This experiment was successful without noticeable fouling and with acceptable emissions levels	(Czernik and Bridgwater 2004)
Aston University	UK	CHP engine	400 kW	Bio-oil	Liquid biofuels produced through pyrolysis can be used in internal and external combustion engines and look promising to replace fossil diesel use in compression-ignition engines. Work is currently being done on upgrading bio-oils and modifying the engine to improve the quality and performance of the biofuels-based CHP operation.	(Yang et al. 2017)
Iowa State University	USA	Heating boiler	600 kW	Bio-oil	Combustion tests were conducted in the boiler using #2 fuel oil, natural gas, pyrolysis oil, and mixtures of ethanol and pyrolysis oil. Data show the feasibility, range of conditions, and fuel injection strategies for clean combustion of bio-oil and displacement of natural gas or fuel oil in large-scale commercial boilers.	(Redfern 2013)
University of North Carolina	USA		Ten hp	Bio-oil	A "compression ignition" engine test cell was used. The performance of bio-oil was comparable to that of commercial diesel, and it was superior to diesel in terms of fuel consumption at moderate load conditions.	(Sriram 2016)
University of Rostock	Germany	Gas turbine	1.9 MW	bio-oil	Performed in dual fuel mode to allow the combustion of both diesel and bio-oil fuels. The turbine was able to combust the dual-fuel mix, but deposits on the turbine blades were observed, limiting the direct application of this approach	(Czernik and Bridgwater 2004)
Orenda Aerospace Corporation	Canada	Turbine engine	2.5 MWe	bio-oil	Gas turbines running on pyrolysis bio-oils have been developed. Since 1995, Orenda Aerospace Corporation has performed long-term research on the use of turbines fueled by bio-oil. They successfully fueled a 2.5 MWe turbine engine designed by the Ukrainian company Mashproekt that incorporates a relatively open combustion chamber that allows ease of modification to accommodate various fuel types. Tests were performed with no adverse effects noted.	(Czernik and Bridgwater 2004)
Red Arrow	USA	Heating plant	5 MWth	pyrolytic lignin	This Wisconsin company that manufactures liquid smoke flavorings from bio-oil combusts the pyroligneous byproduct of their process combined with char and non-condensable exit gases to provide their process heat. The bio-oil is combusted at an air-atomizing nozzle with the char and gas input separately. This combustion boiler has successfully operated in this mode for many years	(Czernik and Bridgwater 2004)
Oilon Oy	Finland	Furnace	4 MWth	bio-oil	The results of these tests showed that some minor modifications of burner and boiler are required to replace petroleum fuels with bio-oil; a petroleum fuel was required for ignition; emissions are lower for all emissions except particulates	(Czernik and Bridgwater 2004)
Manitowoc power station	USA	Commercial production of electricity	20 MWe	co-fired with coal	Electricity generation was demonstrated for a 370-hour test using a 20 MWe boiler. No modifications of the boiler were required, and test results indicated proper combustion with no operational or emissions issues	(Czernik and Bridgwater 2004)

Company	Country	Process	Scale	Type	Remarks	References
VTT Energy	Finland	Diesel Engine	4.8 kW and 84 kWe	Bio-oil	Tests with medium-speed diesel engines allowed raw bio-oil to be combusted with pilot ignition. However, injection adjustment during combustion was difficult, and injection and pump elements suffered rapid wear and corrosion.	(Czernik and Bridgwater 2004)
The University of Kansas	USA	Diesel Engine	Lab Engine	bio-oil and methanol	An air-cooled Lister Petter diesel engine that was fueled with hot-filtered bio-oil provided performance equivalent to that of petroleum diesel. Raw bio-oils would perform best in low-speed diesel engines with high compression ratios.	(Czernik and Bridgwater 2004)
MIT	USA	Diesel Engine	Lab Engine		With a single-cylinder, the direct-injection engine, testers found that the raw bio-oil must be preheated to 55°C for proper ignition, but it combusted well after this step.	(Czernik and Bridgwater 2004)
Ormrod Diesels	UK	Diesel Engine	250 kWe		It was necessary to use diesel for ignition to start the engine. Deposits were noted on the pumps and injectors, but no adverse effect on engine performance resulted.	(Czernik and Bridgwater 2004)
Pasquali Macchine Agricole	Italy	Diesel Engine	6.25 kW		Tests successfully combusted emulsions containing up to 50% raw bio-oil. However, injectors sustained damage worse than previous researchers noted for diesel combustion of raw bio-oil.	(Czernik and Bridgwater 2004)

Appendix D – Feedstocks Calculation Example (New England) for Six Options to Produce Bio-Oil or Biocrude

Option Description	Product Derating / Percent Reduction of Power Output	Amount of Product Needed (quadrillion Btu)	Amount of Product Needed (metric tons)	Total Feedstock Needed (metric tons)
Pyrolysis Bio-Oil from Clean Wood (Yield from pine wood = 64%) for New England census division	48	0.02049	954,935	1,492,086
HTL Biocrude from Clean Wood (Yield from pine wood = 29%) for New England census division	37	0.0190	726,813	2,472,154
Pyrolysis Bio-Oil from Forest Residues (Yield from Forest Residues = 51%) for New England census division	48	0.02049	954,935	1,890,960
HTL Biocrude from Forest Residues (Yield from Forest Residues = 37%) for New England census division	37	0.0190	726,813	1,980,418
Pyrolysis Bio-Oil from Corn Stover (Yield from Corn Stover = 56%) for New England census division	48	0.02049	954,935	1,696,154
HTL Biocrude from Corn Stover (Yield from Corn Stover = 25% for New England census division	37	0.0190	726,813	2,907,253

Note: Petroleum liquids consumption for electricity generation (based on fuel oil 2018) is 2,204 thousands of barrels (0.0139 quadrillion Btu).

Appendix E – Dry Feedstocks Needed (tonne/yr) by Census Division for Six Options of Feedstock Supply

Census Division	Biofuels	Bio-oil			Biocrude		
	Petroleum Liquids Consumption for electricity generation (All sectors) (2018)[(a)]	Dry Clean Wood needed (Yield from pine wood = 64%)[(b)]	Dry Forest Residues needed (Yield from Forest Residues = 51%)[(b)]	Dry Corn Stover needed (Yield from Corn Stover = 54%)[(c)]	Dry Clean Wood needed (Yield from pine wood = 29%)[(f)]	Dry Forest Residues needed (Yield from Forest Residues = 37%)[(e)]	Dry Corn Stover needed (Yield from Corn Stover = 25%)[(f)]
	(thousand barrels)	(metric ton)	(metric ton)	(metric ton)	(metric ton)	(metric ton)	(metric ton)
New England	2,204	1,492,086	1,890,960	1,696,154	2,472,154	1,980,418	2,907,253
Middle Atlantic	3,912	2,648,385	3,356,369	3,010,597	4,387,961	3,515,152	5,160,243
East North Central	1,080	731,149	926,605	831,146	1,211,400	970,441	1,424,607
West North Central	625	423,119	536,230	480,988	701,042	561,598	824,425
South Atlantic	5,506	3,727,506	4,723,969	4,237,308	6,175,899	4,947,450	7,262,857
East South Central	603	408,225	517,354	464,057	676,365	541,829	795,405
West South Central	286	193,619	245,379	220,100	320,797	256,987	377,257
Mountain	366	247,778	314,016	281,666	410,530	328,872	482,783
Pacific Contiguous	169	114,411	144,996	130,059	189,562	151,856	222,925
Pacific Noncontiguous	12,494	8,458,312	10,719,445	9,615,133	14,014,108	11,226,561	16,480,591

(a) (EIA n.d.-a)
(b) (Oasmaa et al. 2010)
(c) (Wright et al. 2010a)
(d) (Zhu et al. 2014)
(e) (Nie and Bi 2018)
(f) (Collett et al. 2019)

Appendix F – Values for Corn Stover at 100-Dry-Metric-Ton/Day Biorefineries

	Options	Bi-Oil: Dry Corn Stover ($/dry tonne)			Biocrude: Dry Corn Stover ($/dry tonne)		
		Biorefinery capacity 100 dt/day	Biorefinery capacity 500 dt/day	Biorefinery capacity 1,000 dt/day	Biorefinery capacity 100 dt/day	Biorefinery capacity 500 dt/day	Biorefinery capacity 1,000 dt/day
	No. of biorefineries	46	9	5	80.0	16	8
New England	$/metric ton	(Corn stover is scarce in New England)					
	No. of biorefineries	82	16	8	141	28	14
Middle Atlantic	$/metric ton	45 biorefineries, $90–$155, avg $105			45 biorefineries, $90–$155, avg $105		
	No. of biorefineries	23	5	2	39	8	4
East North Central	$/metric ton	$88–$89, avg $89			$88-$90, avg $89		
	No. of biorefineries	13	3	1	23	5	2
West North Central	$/metric ton	$71–$72, avg $72			$71–$73, avg $72		
	No. of biorefineries	116	23	12	199	40	20
South Atlantic	$/metric ton	33 biorefineries, $91–$166, avg $105			33 biorefineries, $91–$166, avg $105		
	No. of biorefineries	13	3	1	22	4	2
East South Central	$/metric ton	$90–$96, avg $93			$90–$98, avg $95		
	No. of biorefineries	6	1	1	10	2	1
West South Central	$/metric ton	$72–$76, avg $74			$72–$79, avg $76		
	No. of biorefineries	8	2	1	13	3	1
Mountain	$/metric ton	$80–$87, avg $84			$80–$90, avg $86		
	No. of biorefineries	4	1	0	6	1	1
Pacific Contiguous	$/metric ton	$83–$86, avg $85			$83–$87, avg $85		
Pacific Noncontiguous	No. of biorefineries	263	53	26	452	90	45
	$/metric ton	(Corn stover is scarce in Pacific Noncontiguous)					

Appendix G – Potential Number of Bio-Oil or Biocrude Biorefineries per Census Division according to Annual Feedstocks for Four Plant Capacities

		Bio-oil			Biocrude		
		Dry Clean Wood[a] (Yield from pine = 64%)	Dry Forest Residues[a] (Yield = 51%)	Dry Corn Stover[b] (Yield = 54%)	Dry Clean Wood[c] (Yield from pine = 29%)	Dry Forest Residues[d] (Yield = 37%)	Dry Corn Stover[e] (Yield = 25%)
	Census Division	MT Feedstock/ No. of Plants	MT Feedstock/ No. of Plants	MT Feedstock/ No. of Plants	MT Feedstock/ No. of Plants	MT Feedstock/ No. of Plants	MT Feedstock/ No. of Plants
1	**New England**	1,492,086	1,890,960	1,696,154	2,472,154	1,980,418	2,907,253
	Plant capacity 2000 dt/d	2	3	2	3	3	4
	Plant capacity 1000 dt/d	4	5	5	7	5	8
	Plant capacity 500 dt/d	8	10	9	14	11	16
	Plant capacity 100 dt/d	41	52	46	68	54	80
2	**Middle Atlantic**	2,648,385	3,356,369	3,010,597	4,387,961	3,515,152	5,160,243
	Plant capacity 2000 dt/d	4	5	4	6	5	7
	Plant capacity 1000 dt/d	7	9	8	12	10	14
	Plant capacity 500 dt/d	15	18	16	24	19	28
	Plant capacity 100 dt/d	73	92	82	120	96	141
3	**East North Central**	731,149	926,605	831,146	1,211,400	970,441	1,424,607
	Plant capacity 2000 dt/d	1	1	1	2	1	2
	Plant capacity 1000 dt/d	2	3	2	3	3	4
	Plant capacity 500 dt/d	4	5	5	7	5	8
	Plant capacity 100 dt/d	20	25	23	33	27	39
4	**West North Central**	423,119	536,230	480,988	701,042	561,598	824,425
	Plant capacity 2000 dt/d	1	1	1	1	1	1
	Plant capacity 1000 dt/d	1	1	1	2	2	2
	Plant capacity 500 dt/d	2	3	3	4	3	5
	Plant capacity 100 dt/d	12	15	13	19	15	23
5	**South Atlantic**	3,727,506	4,723,969	4,237,308	6,175,899	4,947,450	7,262,857
	Plant capacity 2000 dt/d	5	6	6	8	7	10

	Census Division	Bio-oil: Dry Clean Wood[a] (Yield from pine = 64%) MT Feedstock/ No. of Plants	Bio-oil: Dry Forest Residues[a] (Yield = 51%) MT Feedstock/ No. of Plants	Bio-oil: Dry Corn Stover[b] (Yield = 54%) MT Feedstock/ No. of Plants	Biocrude: Dry Clean Wood[c] (Yield from pine = 29%) MT Feedstock/ No. of Plants	Biocrude: Dry Forest Residues[d] (Yield = 37%) MT Feedstock/ No. of Plants	Biocrude: Dry Corn Stover[e] (Yield = 25%) MT Feedstock/ No. of Plants
	Plant capacity 1000 dt/d	10	13	12	17	14	20
	Plant capacity 500 dt/d	20	26	23	34	27	40
	Plant capacity 100 dt/d	102	129	116	169	136	199
6	**East South Central**	408,225	517,354	464,057	676,365	541,829	795,405
	Plant capacity 2000 dt/d	1	1	1	1	1	1
	Plant capacity 1000 dt/d	1	1	1	2	1	2
	Plant capacity 500 dt/d	2	3	3	4	3	4
	Plant capacity 100 dt/d	11	14	13	19	15	22
7	**West South Central**	193,619	245,379	220,100	320,797	256,987	377,257
	Plant capacity 2000 dt/d	0	0	0	0	0	1
	Plant capacity 1000 dt/d	1	1	1	1	1	1
	Plant capacity 500 dt/d	1	1	1	2	1	2
	Plant capacity 100 dt/d	5	7	6	9	7	10
8	**Mountain**	247,778	314,016	281,666	410,530	328,872	482,783
	Plant capacity 2000 dt/d	0	0	0	1	0	1
	Plant capacity 1000 dt/d	1	1	1	1	1	1
	Plant capacity 500 dt/d	1	2	2	2	2	3
	Plant capacity 100 dt/d	7	9	8	11	9	13
9	**Pacific Contiguous**	114,411	144,996	130,059	189,562	151,856	222,925
	Plant capacity 2000 dt/d	0	0	0	0	0	0
	Plant capacity 1000 dt/d	0	0	0	1	0	1
	Plant capacity 500 dt/d	1	1	1	1	1	1
	Plant capacity 100 dt/d	3	4	4	5	4	6
10	**Pacific Noncontiguous**	8,458,312	10,719,445	9,615,133	14,014,108	11,226,561	16,480,591
	Plant capacity 2000 dt/d	12	15	13	19	15	23
	Plant capacity 1000 dt/d	23	29	26	38	31	45

	Census Division	Bio-oil: Dry Clean Wood[a] (Yield from pine = 64%) MT Feedstock/ No. of Plants	Bio-oil: Dry Forest Residues[a] (Yield = 51%) MT Feedstock/ No. of Plants	Bio-oil: Dry Corn Stover[b] (Yield = 54%) MT Feedstock/ No. of Plants	Biocrude: Dry Clean Wood[c] (Yield from pine = 29%) MT Feedstock/ No. of Plants	Biocrude: Dry Forest Residues[d] (Yield = 37%) MT Feedstock/ No. of Plants	Biocrude: Dry Corn Stover[e] (Yield = 25%) MT Feedstock/ No. of Plants
	Plant capacity 500 dt/d	46	59	53	77	62	90
	Plant capacity 100 dt/d	232	294	263	384	308	452
U.S.	**US Total**	18,444,590	23,375,323	20,967,208	30,559,818	24,481,164	35,938,346
	Plant capacity 2000 dt/d	25	32	29	42	34	49
	Plant capacity 1000 dt/d	51	64	57	84	67	98
	Plant capacity 500 dt/d	101	128	115	167	134	197
	Plant capacity 100 dt/d	505	640	574	837	671	985

(a) (Oasmaa and Peacocke 2010)
(b) (Wright et al. 2010b)
(c) (Zhu et al. 2014)
(d) (Nie and Bi 2018)
(e) (Collett et al. 2019)

Appendix H – Annual Availability of Clean Wood and Forest Residues by Census Division (dry tonnes/year) and Cost

Region / Feedstock	$30/DMT	$40/DMT	$50/DMT	$60/DMT	$70/DMT	$80/DMT	$90/DMT	$100/DMT
East North Central	**1,991,958**	**1,991,958**	**3,803,593**	**5,877,985**	**11,554,773**	**11,554,773**	**11,554,773**	**11,554,773**
Hardwood residues	1,804,437	1,804,437	1,804,437	1,804,437	1,804,437	1,804,437	1,804,437	1,804,437
Hardwood whole trees			1,387,562	3,448,983	7,433,476	7,433,476	7,433,476	7,433,476
Mixed wood residues	66,237	66,237	66,237	66,237	66,237	66,237	66,237	66,237
Mixed wood whole trees			11,177	15,539	459,039	459,039	459,039	459,039
Softwood residues	121,284	121,284	121,284	121,284	121,284	121,284	121,284	121,284
Softwood whole trees			412,896	421,505	1,670,300	1,670,300	1,670,300	1,670,300
East South Central	**3,578,680**	**3,809,255**	**9,435,592**	**16,645,328**	**16,645,328**	**16,645,328**	**16,645,328**	**16,645,328**
Hardwood residues	1,189,418	1,189,418	1,189,418	1,189,418	1,189,418	1,189,418	1,189,418	1,189,418
Hardwood whole trees		21,155	1,039,164	7,732,847	7,732,847	7,732,847	7,732,847	7,732,847
Mixed wood residues	1,079,155	1,079,155	1,079,155	1,079,155	1,079,155	1,079,155	1,079,155	1,079,155
Mixed wood whole trees		72,087	244,123	279,551	279,551	279,551	279,551	279,551
Softwood residues	1,310,107	1,310,107	1,310,107	1,310,107	1,310,107	1,310,107	1,310,107	1,310,107
Softwood whole trees		137,333	4,573,625	5,054,250	5,054,250	5,054,250	5,054,250	5,054,250
Middle Atlantic	**608,303**	**608,303**	**1,368,187**	**2,486,440**	**7,255,913**	**7,255,913**	**7,255,913**	**7,255,913**
Hardwood residues	447,848	447,848	447,848	447,848	447,848	447,848	447,848	447,848
Hardwood whole trees			693,033	1,636,147	5,890,225	5,890,225	5,890,225	5,890,225
Mixed wood residues	143,937	143,937	143,937	143,937	143,937	143,937	143,937	143,937
Mixed wood whole trees			16,949	85,926	87,036	87,036	87,036	87,036
Softwood residues	16,518	16,518	16,518	16,518	16,518	16,518	16,518	16,518
Softwood whole trees			49,902	156,064	670,349	670,349	670,349	670,349
Mountain	**685,184**	**694,603**	**4,190,547**	**7,897,026**	**8,416,291**	**8,416,291**	**8,416,291**	**8,416,291**
Hardwood residues	15,537	15,537	15,537	15,537	15,537	15,537	15,537	15,537

Region / Feedstock	$30/DMT	$40/DMT	$50/DMT	$60/DMT	$70/DMT	$80/DMT	$90/DMT	$100/DMT
Hardwood whole trees			116,809	709,912	1,229,177	1,229,177	1,229,177	1,229,177
Softwood residues	669,647	669,647	669,647	669,647	669,647	669,647	669,647	669,647
Softwood whole trees		9,419	3,388,554	6,501,930	6,501,930	6,501,930	6,501,930	6,501,930
New England	**807,659**	**807,659**	**3,253,082**	**4,838,827**	**11,367,593**	**11,367,593**	**11,367,593**	**11,367,593**
Hardwood residues	374,061	374,061	374,061	374,061	374,061	374,061	374,061	374,061
Hardwood whole trees			1,485,377	3,054,148	8,081,475	8,081,475	8,081,475	8,081,475
Mixed wood residues	243,446	243,446	243,446	243,446	243,446	243,446	243,446	243,446
Mixed wood whole trees			3,104	3,104	3,104	3,104	3,104	3,104
Softwood residues	190,152	190,152	190,152	190,152	190,152	190,152	190,152	190,152
Softwood whole trees			956,942	973,916	2,475,355	2,475,355	2,475,355	2,475,355
Pacific Contiguous	**1,722,507**	**1,722,507**	**6,860,684**	**15,321,553**	**15,563,303**	**15,563,303**	**15,563,303**	**15,563,303**
Hardwood residues	188,785	188,785	188,785	188,785	188,785	188,785	188,785	188,785
Hardwood whole trees				3,138,447	3,380,197	3,380,197	3,380,197	3,380,197
Softwood residues	1,533,722	1,533,722	1,533,722	1,533,722	1,533,722	1,533,722	1,533,722	1,533,722
Softwood whole trees			5,138,177	10,460,599	10,460,599	10,460,599	10,460,599	10,460,599
South Atlantic	**5,324,553**	**6,066,593**	**17,679,513**	**26,141,737**	**27,806,837**	**27,806,837**	**27,806,837**	**27,806,837**
Hardwood residues	1,487,942	1,487,942	1,487,942	1,487,942	1,487,942	1,487,942	1,487,942	1,487,942
Hardwood whole trees		106,810	1,740,661	8,746,370	10,163,846	10,163,846	10,163,846	10,163,846
Mixed wood residues	1,683,617	1,683,617	1,683,617	1,683,617	1,683,617	1,683,617	1,683,617	1,683,617
Mixed wood whole trees		320,018	1,293,160	1,623,386	1,644,665	1,644,665	1,644,665	1,644,665
Softwood residues	2,152,994	2,152,994	2,152,994	2,152,994	2,152,994	2,152,994	2,152,994	2,152,994
Softwood whole trees		315,212	9,321,139	10,447,428	10,673,773	10,673,773	10,673,773	10,673,773
West North Central	**1,250,577**	**1,255,052**	**2,742,209**	**4,083,974**	**6,380,401**	**6,380,401**	**6,380,401**	**6,380,401**
Hardwood residues	992,715	992,715	992,715	992,715	992,715	992,715	992,715	992,715
Hardwood whole trees			1,045,178	2,265,628	3,937,622	3,937,622	3,937,622	3,937,622

Region / Feedstock	$30/DMT	$40/DMT	$50/DMT	$60/DMT	$70/DMT	$80/DMT	$90/DMT	$100/DMT
Mixed wood residues	113,922	113,922	113,922	113,922	113,922	113,922	113,922	113,922
Mixed wood whole trees			87,402	116,552	157,434	157,434	157,434	157,434
Softwood residues	143,940	143,940	143,940	143,940	143,940	143,940	143,940	143,940
Softwood whole trees		4,475	359,052	451,217	1,034,768	1,034,768	1,034,768	1,034,768
West South Central	**2,625,316**	**3,202,033**	**6,153,248**	**11,009,491**	**11,009,491**	**11,009,491**	**11,009,491**	**11,009,491**
Hardwood residues	771,467	771,467	771,467	771,467	771,467	771,467	771,467	771,467
Hardwood whole trees		12,022	915,230	5,640,724	5,640,724	5,640,724	5,640,724	5,640,724
Mixed wood residues	736,388	736,388	736,388	736,388	736,388	736,388	736,388	736,388
Mixed wood whole trees		12,436	559,601	665,978	665,978	665,978	665,978	665,978
Softwood residues	1,117,461	1,117,461	1,117,461	1,117,461	1,117,461	1,117,461	1,117,461	1,117,461
Softwood whole trees		552,259	2,053,101	2,077,473	2,077,473	2,077,473	2,077,473	2,077,473

Appendix I – Conceptual Design Summary

HTL Biocrude From Biomass
Conceptual Design Summary

All Values in 2016$

Minimum Fuel Selling Price (MFSP)	**$4.79**	**$/gallon biocrude**
	$4.85	$/gge
Pyrolysis Oil Production	3	million gallons/year
Pyrolysis Oil Yield	86	gallons/dry US ton wood
Feedstock + Handling Cost	84.45	$/dry short ton feed
Dry Biomass Feedstock Rate	100	metric tons/day
Internal Rate of Return (After-Tax)	10%	
Equity Percent of Total Investment	40%	
On-Stream Factor	90%	

Capital Costs - millions USD	
Fast Pyrolysis & Quench	$2
Filtration	$21
Balance of Plant	$1
Total Installed Equipment Cost	$24
Fixed Capital Investment (FCI)	$57
Working Capital	$3
Land	$0.5
Total Capital Investment	$60
Installed Capital/Annual Gallon Pyrolysis Oil	7.8
TCI/Annual Gallon Pyrolysis Oil	19.4
Loan Rate	8.0%
Term (years)	10

Performance	
Plant Purchased Electricity (KWh/gal pyrolysis oil)	3.56
Water Usage (gallons/gal pyrolysis oil)	5.01

Manufacturing Costs ($/Gallon)	
Feedstock + Handling	0.99
Catalysts & Chemicals	0.04
Waste Disposal	0.07
Electricity and other utilities	0.25
Fixed Costs	1.65
Capital Depreciation	0.61
Average Income Tax	0.18
Average Return on Investment	1.00
	4.79

Manufacturing Costs ($/yr)	
Feedstock + Handling	$3,100,000
Catalysts & Chemicals	100,000
Waste Disposal	$200,000
Electricity and other utilities	$800,000
Fixed Costs	$5,100,000
Capital Depreciation	$1,900,000
Average Income Tax	$600,000
Average Return on Investment	$3,200,000

HTL Biocrude From Biomass
Conceptual Design Summary

All Values in 2016$

Minimum Fuel Selling Price (MFSP)	**$3.10**	**$/gallon biocrude**
	$3.13	$/gge
Pyrolysis Oil Production	62	million gallons/year
Pyrolysis Oil Yield	86	gallons/dry US ton wood
Feedstock + Handling Cost	84.45	$/dry short ton feed
Dry Biomass Feedstock Rate	2,000	metric tons/day
Internal Rate of Return (After-Tax)	10%	
Equity Percent of Total Investment	40%	
On-Stream Factor	90%	

Capital Costs - millions USD	
Fast Pyrolysis & Quench	$10
Filtration	$272
Balance of Plant	$5
Total Installed Equipment Cost	$288
Fixed Capital Investment (FCI)	$654
Working Capital	$33
Land	$0.5
Total Capital Investment	$687
Installed Capital/Annual Gallon Pyrolysis Oil	4.6
TCI/Annual Gallon Pyrolysis Oil	11.1
Loan Rate	8.0%
Term (years)	10

Performance	
Plant Purchased Electricity (KWh/gal pyrolysis oil)	3.32
Water Usage (gallons/gal pyrolysis oil)	5.01

Manufacturing Costs ($/Gallon)	
Feedstock + Handling	0.99
Catalysts & Chemicals	0.04
Waste Disposal	0.02
Electricity and other utilities	0.23
Fixed Costs	0.46
Capital Depreciation	0.35
Average Income Tax	0.10
Average Return on Investment	0.91
	3.10

Manufacturing Costs ($/yr)	
Feedstock + Handling	$61,200,000
Catalysts & Chemicals	2,500,000
Waste Disposal	$1,300,000
Electricity and other utilities	$14,300,000
Fixed Costs	$28,300,000
Capital Depreciation	$21,800,000
Average Income Tax	$6,400,000
Average Return on Investment	$56,500,000

Pyrolysis Oil From Biomass
Conceptual Design Summary

All Values in 2016$

Minimum Fuel Selling Price (MFSP) **$1.83 $/gallon pyrolysis oil**

Pyrolysis Oil Production	6	million gallons/year
Pyrolysis Oil Yield	168	gallons/dry US ton wood
Feedstock + Handling Cost	84.45	$/dry short ton feed
Dry Biomass Feedstock Rate	**100**	metric tons/day
Internal Rate of Return (After-Tax)	10%	
Equity Percent of Total Investment	40%	
On-Stream Factor	90%	

Capital Costs - millions USD	
Fast Pyrolysis & Quench	$15
Filtration	$0
Balance of Plant	$1
Total Installed Equipment Cost	$16
Fixed Capital Investment (FCI)	$27
Working Capital	$1
Land	$0.5
Total Capital Investment	$29
Installed Capital/Annual Gallon Pyrolysis Oil	2.6
TCI/Annual Gallon Pyrolysis Oil	4.8
Loan Rate	8.0%
Term (years)	10

Performance	
Plant Purchased Electricity (KWh/gal pyrolysis oil)	0.70
Water Usage (gallons/gal pyrolysis oil)	0.15

Manufacturing Costs ($/Gallon)	
Feedstock + Handling	0.50
Catalysts & Chemicals	0.00
Waste Disposal	0.00
Electricity and other utilities	0.05
Fixed Costs	0.65
Capital Depreciation	0.15
Average Income Tax	0.05
Average Return on Investment	0.43
	1.83

Manufacturing Costs ($/yr)	
Feedstock + Handling	$3,100,000
Catalysts & Chemicals	0
Waste Disposal	$0
Electricity and other utilities	$300,000
Fixed Costs	$4,000,000
Capital Depreciation	$900,000
Average Income Tax	$300,000
Average Return on Investment	$2,600,000

Pyrolysis Oil From Biomass
Conceptual Design Summary

All Values in 2016$

Minimum Fuel Selling Price (MFSP) **$0.95 $/gallon pyrolysis oil**

Pyrolysis Oil Production	121 million gallons/year
Pyrolysis Oil Yield	168 gallons/dry US ton wood
Feedstock + Handling Cost	84.45 $/dry short ton feed
Dry Biomass Feedstock Rate	**2,000** metric tons/day
Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%
On-Stream Factor	90%

Capital Costs - millions USD	
Fast Pyrolysis & Quench	$151
Filtration	$0
Balance of Plant	$3
Total Installed Equipment Cost	$155
Fixed Capital Investment (FCI)	$265
Working Capital	$13
Land	$0.5
Total Capital Investment	$278
Installed Capital/Annual Gallon Pyrolysis Oil	1.3
TCI/Annual Gallon Pyrolysis Oil	2.3
Loan Rate	8.0%
Term (years)	10

Performance	
Plant Purchased Electricity (KWh/gal pyrolysis oil)	0.70
Water Usage (gallons/gal pyrolysis oil)	0.15

Manufacturing Costs ($/Gallon)	
Feedstock + Handling	0.50
Catalysts & Chemicals	0.00
Waste Disposal	0.00
Electricity and other utilities	0.05
Fixed Costs	0.11
Capital Depreciation	0.07
Average Income Tax	0.02
Average Return on Investment	0.20
	0.95

Manufacturing Costs ($/yr)	
Feedstock + Handling	$61,200,000
Catalysts & Chemicals	0
Waste Disposal	$400,000
Electricity and other utilities	$5,900,000
Fixed Costs	$13,200,000
Capital Depreciation	$8,800,000
Average Income Tax	$2,600,000
Average Return on Investment	$23,800,000

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